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# THERMOMECHANICAL AND FRACTURE ANALYSIS OF SILICON CARBIDE IN CANNON BORE APPLICATIONS

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13. ABSTRACT *(Maximum 200 words)*
A 200 $W/mm^2$ heat flux typical of cannon bore heating is applied to a silicon carbide (SiC) sample using pulsed laser heating that simulates cannon firing. Thermomechanical models of the near-bore failure processes in fired chromium plated steel cannons are adapted to evaluate SiC for potential use in cannon bore applications. Near-bore transient temperatures are calculated using a finite-difference method and validated using the observed depth and known temperature of the steel transformation. Cracks both normal and parallel to the heated surface are noted in the SiC sample to a depth of 0.08-mm following 5-ms pulses of laser heating. The cracking is attributed to similar mechanisms as those in cannons, i.e., transient thermal expansion and permanent compressive deformation at high temperature followed by thermal contraction and tensile residual stresses upon cooling. Fracture analysis shows that the 0.08-mm deep cracks would lead to further cracking of the SiC upon application of cannon firing pressures.

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## INTRODUCTION

Firing damage in cannons has typically been mechanical in nature, including wear and fatigue cracking and the occasional fast, fragmentation failure, after wear or fatigue has initiated damage. Recently, the desire for increased cannon performance has led to higher and more sustained temperatures at the cannon bore, and the chromium coating applied to retard wear is sustaining critical thermal damage. In recent work (refs 1-3), actual and simulated cannon firing damage has been characterized and modeled to determine the coating materials and processes that could better withstand thermal damage in modern cannon firing. Electroplated chromium, currently used in cannons, and sputtered tantalum have been studied following both proving ground firing and laser heating simulation of firing. Thermomechanical models have been developed to determine near-bore transient temperatures and the transient and residual thermally-generated stresses that control failure in thermally damaged segments of bore coating.

This case study describes and models thermal damage in a sample of alpha SiC following laser heating that simulates cannon firing, and compares the SiC results with those from chromium coated steel subjected to firing and laser-simulated firing. The results are interpreted in relation to cannon applications, including a fracture mechanics assessment of thermally damaged SiC at the bore of a cannon.

## LASER SIMULATION OF CANNON FIRING DAMAGE

Figure 1 is a metallographic cross section of a chromium plated A723 steel sample that has been laser heated to simulate cannon firing. Twenty 5-ms laser pulses (ref 3) were applied with about 1 J/mm$^2$ heat input during each pulse, which corresponds to 200 W/mm$^2$ heat flux, typical for tank cannon firing. Note that this is considerably higher than the 1 W/mm$^2$ heat flux for typical gas turbine applications (ref 4). The key features of laser thermal damage are similar to those observed from firing damage (refs 1,2). They are, from top to bottom in Figure 1:

- The 1320°K recrystallization and grain growth of chromium, to a 0.05-mm depth in the case here
- Cracks through the chromium and continuing into the steel
- The 1020°K steel transformation, to a depth 0.17-mm below the surface.

These features, particularly the steel transformation, are used in the development of the thermal damage model for a cannon bore coating, discussed next.

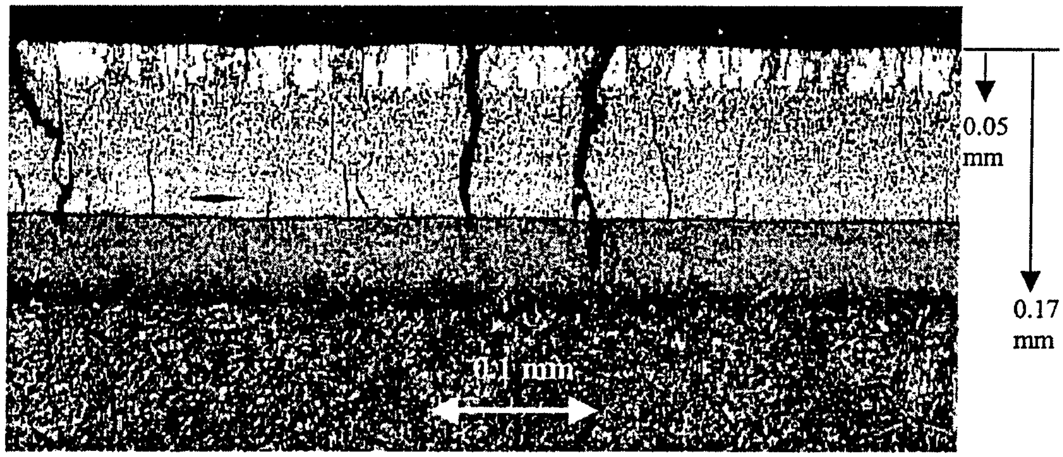


Figure 1. Near-surface thermal damage in laser-heated chromium plated steel sample #L1.

## THERMAL DAMAGE MODEL FOR A CANNON COATING

The model calculates near-bore maximum transient temperatures and the resultant transient and residual thermally-generated stresses in a cannon bore coating. Details are given in prior work.(refs 1,2), so only a brief description is given here. Near-bore temperatures are determined from a spreadsheet finite-difference method using, as inputs, temperature-dependent thermal properties of chromium coating and steel, the coating thickness, the cannon gas temperature, the duration of the gas pulse, and its convection coefficient. Transient and residual stresses are determined from the finite-difference temperatures using conventional solid mechanics relations and properties, including Poisson's ratio, thermal expansion, and temperature-dependent elastic modulus and yield strength. Key model inputs and results are listed in Table 1 for three model calculations:

- Sample #F26 from prior work (ref 1) taken directly from a fired tank cannon
- Sample #L1 for the laser-heating simulation of firing damage shown in Figure 1
- Sample SiC for a similar level of laser heating applied to a silicon carbide sample, discussed in the next section.

**Table 1. Inputs/Results of Thermomechanical Analysis of Firing and Laser Damage**

| Sample/Heating | $h$ (mm) | $T_{GAS}$ (°K) | $T_{SURFACE}$ (°K) | Heat Input (J/mm$^2$) | Depth of Tensile Residual Stress (mm) |
|---|---|---|---|---|---|
| #F26/Fired | 0.12 | 2660 | 1620 | 1.33 | 0.5 |
| #L1/Laser | 0.11 | 2480 | 1530 | 1.22 | 0.6 |
| SiC/Laser | -- | 2660 | 1700 | 1.23 | 0.05 to 0.08 |

In Table 1, $h$ is the thickness of the chromium coating, $T_{GAS}$ is the gas temperature, and $T_{SURFACE}$ is the maximum temperature at the heated surface. Note that for samples F26 and L1, $T_{GAS}$ is the model input at which the *calculated* depth corresponding to 1020°K in the model matches the *observed* depth of the 1020°K steel transformation in the sample. For the SiC

sample, the $T_{GAS}$ input was 2660°K, equal to that of #F26, the chromium-steel sample taken from a fired cannon. A discussion of laser thermal damage and modeling for SiC is discussed next.

## THERMAL DAMAGE AND MODEL FOR SiC

Figure 2 is a metallographic cross section of Hexoloy SA SiC that has been laser heated to simulate cannon firing, using ten 5-ms laser pulses at about the same heat input level as that for the chromium-steel sample in Figure 1. There were no obvious transformations as in the chromium-steel sample, but cracking in two orientations can be seen, normal and parallel to the heated surface (at the top of the photo), to a depth of 0.08-mm. The similarity in cracking damage for the chromium-steel and SiC samples was the impetus of the effort here to apply the thermal damage model used for cannon coatings to describe the observed laser thermal damage in SiC.

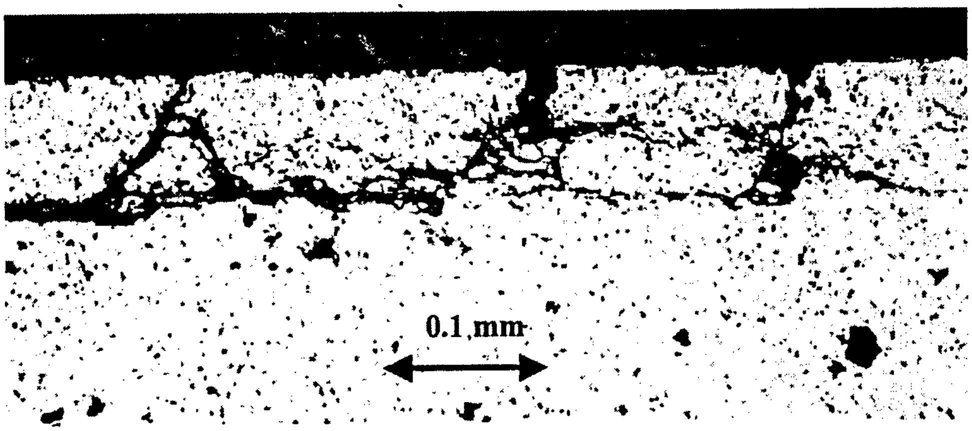


Figure 2. Near-surface thermal damage in laser-heated SiC sample.

Finite-difference modeling of the near-surface transient temperatures for the laser-heated SiC was similar to that for the chromium-steel sample. The same values of convection coefficient (193,000 W/m$^{2\circ}$K), gas temperature (2660°K), and pulse duration (5-ms) were used. Thermal conductivity ($k = 79 - 0.0325T$ in W/m°K) and diffusivity ($\delta = 23 - 0.0108T$ in mm$^2$/s) were based on the higher-temperature data from recent measurements of SiC thermal properties (ref 5).

Equations for the near-bore, transient, in-plane, biaxial compressive thermal stress, $S_T$, and the tensile residual stress, $S_R$, produced when the transient stress exceeds the SiC compressive strength, $S_O$, are as follows:

$$S_T = -E\alpha[T\{x\} - T_i]/[1 - \nu] \qquad (1)$$

$$S_R = -S_T - S_O \qquad \text{for } S_T > S_O \qquad (2)$$

In equation (1): $E$ is elastic modulus, 410 GPa (ref 6); $\alpha$ is thermal expansion coefficient, $5x10^{-6}°K^{-1}$ (ref 6); the transient temperature, $T\{x\}$ from the finite-difference calculations is for a given depth, $x$, below the heated surface; and $\nu$ is Poisson's ratio, 0.19. In equation (2), $S_O$ can be estimated as one-third of hardness (ref 7), so that the temperature-dependent hardness data for SiC (ref 6) provides temperature-dependent values of $S_O$ in the form $S_O = 11{,}700 - 6.4T$ in MPa, for use here.

Results of the transient temperature and transient and residual stress modeling for laser-heated chromium-steel and SiC are shown and compared in Figures 3 and 4. In Figure 3 note that the observed steel damage (at 1020°K and $x = 0.17$-mm) validates the model temperatures, and the observed chromium damage is in reasonable agreement as well. The results in Figures 3 and 4 show similar trends for transient temperature and transient compressive stress, indicating that the thermal and physical properties of SiC ($k$, $\delta$, $E$, $\alpha$, $\nu$) are not significantly different from metals. However, the region in which the transient compressive stress exceeds the elevated-temperature strength of SiC is much closer to the heated surface than is the case for the chromium-steel sample. This results in tensile residual stresses only very near the surface for SiC, due the superior high-temperature strength of SiC compared to steel. Two sets of high-temperature SiC strength data were used for the modeling results in Figure 4, one based on the room temperature $S_O = 9800$ MPa (ref 6), discussed earlier, and the other based on $S_O = 8500$ MPa (ref 7). Note that the depths of residual stress for these two sets of data bracket the 0.08-mm observed crack depth for the SiC sample, indicating that the model provides a good description of thermal damage and tensile residual stress in the laser-heated SiC.

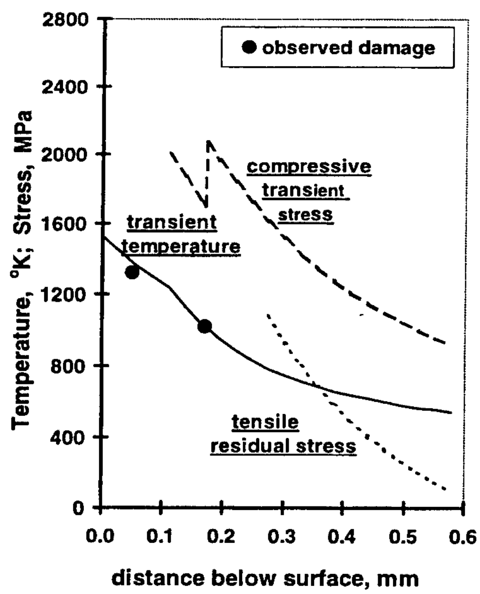


Figure 3. Model results for chromium-steel.

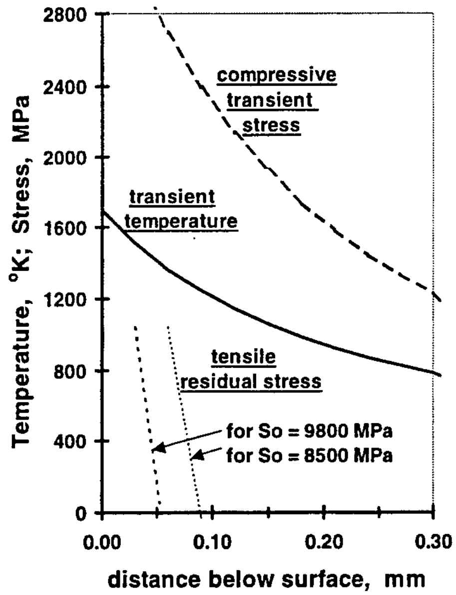


Figure 4. Model results for SiC.

## FRACTURE MECHANICS ANALYSIS

Analysis of a pressurized cannon with thermally cracked SiC at the bore can be done using the shallow crack stress intensity factor expression. At fracture the applied $K = K_{Ic}$, and the near-bore applied $K$ is determined from: crack depth, $a_c$; OD-to-ID ratio, $w$; applied pressure, $p$; and bore residual stress, $S_B$, as follows:

$$K_{Ic} = 1.12(\pi a_c)^{1/2}[(\{w^2 + 1\}/\{w^2 - 1\})p + p + S_B] \qquad (3)$$

Equation (3) was evaluated for typical cannon values of $w = 2$ and $S_B = -900$ MPa to produce the failure predictions shown in Figure 5, that compare the failure behavior of a ceramic-bore tube with that of a steel-bore tube. Note that for a lower-bound $K_{Ic}$ for steel of 90 MPa m$^{1/2}$ and $a_c = 1$-mm, the failure pressure is safely above the cannon firing pressure of 700 MPa. In contrast, for a typical $K_{Ic}$ for SiC of 4 MPa m$^{1/2}$ (ref 6) and $a_c = 0.01$-mm, the failure pressure is below the cannon firing pressure. Recall that the observed crack depth in the laser-heated SiC sample shown in Figure 2 was 0.08-mm, well above the 0.01-mm $a_c$. This indicates that the use of the SiC considered here will result in extensive cracking, initiated by thermal damage and propagated by the cannon firing pressure.

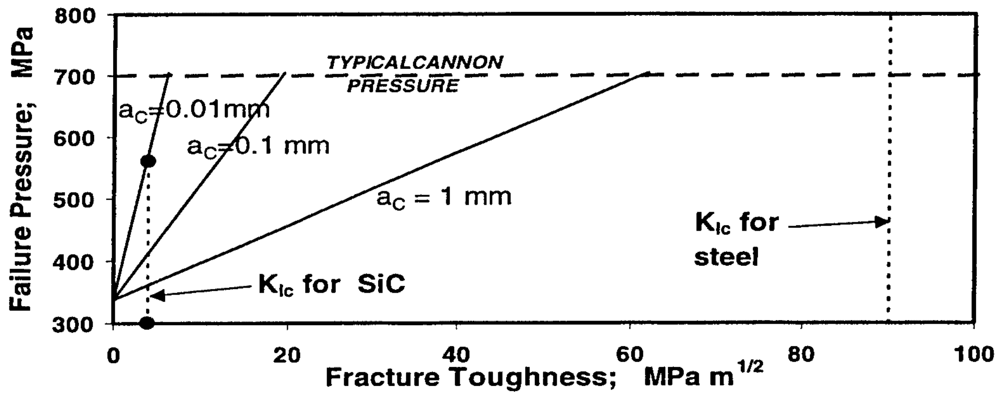


Figure 5. Fracture analysis of pressurized cannon with varying $a_c$ and $K_{Ic}$.

## SUMMARY

Results from this initial case study of a laser-heated SiC sample are as follows. Additional work is underway with replicate samples of SiC and other ceramics.

- A 200 W/mm$^2$ heat flux typical of cannon bore heating applied to an alpha SiC sample using 5-ms pulses of laser heating results in cracks both normal and parallel to the heated surface to a depth of 0.08-mm.

- A thermomechanical model of near-bore transient temperatures and stresses is validated by observed damage in steel cannons and adapted to evaluate SiC for potential use in cannon bore applications.

- Model results indicate that localized near-surface cracking in laser-heated SiC is caused by similar mechanisms as those in cannons, i.e., transient thermal expansion and permanent compressive deformation at high temperature followed by thermal contraction and tensile residual stresses upon cooling.

- Fracture mechanics analysis shows that the 0.08-mm cracks are deeper than the critical depth required for further cracking of the SiC upon application of cannon firing pressures.

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